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IGY GRAVIMETRIC STUDIES AT POLISH ANTARCTIC STATION

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[Following is the translation of an article by Zbigniew Zabek and Janusz Sledzinski in Geodezja i Kartografia (Geodesy and Cartography), Vol IX, No 3/4, Warsaw, July 1960, pages 197-207]

Between December 1958 and March 1959, a gravimetric link was established between Warsaw and the A. B. Dobrowolski Station in Antarctica as part of the Antarctic expedition organized by the IGY Commission of the Presidium of the Polish Academy of Sciences. The measurements were made by the authors of this article, members of the staff of the Department of Advanced Geodetics of the Warsaw Polytechnic.

1) Description of Points Linked

The gravimetric point situated in the gravimetric laboratory of the Department of Advanced Geodetics of the Warsaw Polytechnic, Plac Jednosci Robotniczej 1, Warsaw, was taken as the initial link point. The coordinates of this point are:

$$\varphi = 52^\circ 13' 3'' \text{ N}$$
$$\lambda = 21^\circ 00' 8'' \text{ E}$$
$$H = 114.3 \text{ m npm}$$

The point is one of the main pendulum points in Poland; the value of acceleration due to gravity in the Potsdam system is currently best known in it.

The point established at the A. B. Dobrowolski Station in the Bunger Oasis in Antarctica was stabilized by walling up a pole in the lobby of the seismic pavilion. The pole is set in a rock and protrudes 13 centimeters above the floor. Its coordinates are:

$$\varphi = 66^\circ 16' 3'' \text{S}$$
$$\lambda = 100^\circ 45' 0'' \text{E}$$
$$H = 35.4 \text{ m npm}$$

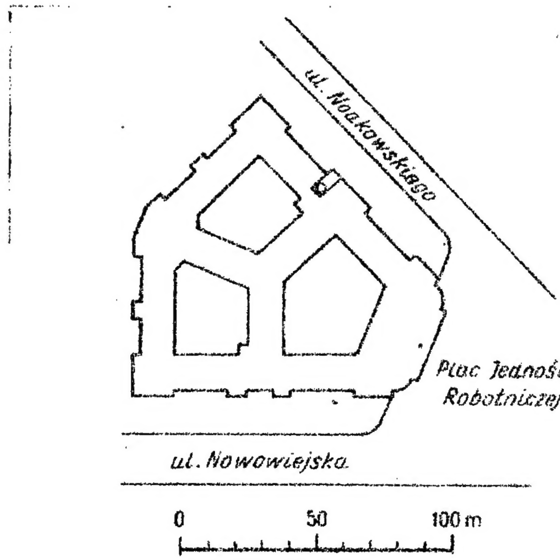

Fig. 1

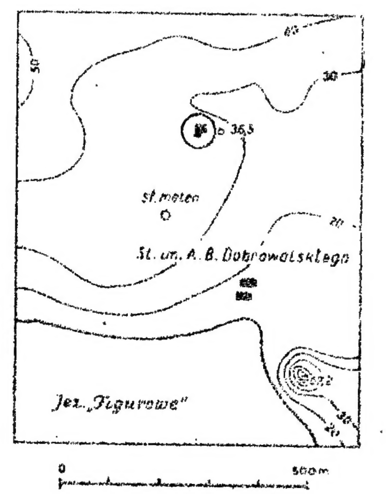

Fig. 2

st. meteo = Meterological
station
St. im A. B. Dobrowolskiego =
A. B. Dobrowolski Station
Jez. "Figurowe = "Figure" Lake

The height of the point was determined by a comparison with the water level of Figure Lake. The height of the water level in the lake relative to the Indian Ocean was taken as 11.6 meters, as established by the Second Soviet Expedition of 1956/1957.

2) Apparatus

The determination of the difference in acceleration was made with a four-pendulum apparatus, manufactured by "Askania" and owned by the Department of Advanced Geodetics of the Warsaw Polytechnic. The apparatus consists of half-second, invar, Sarnecka type pendulums and a photographic recorder which records the pendulums at the instant of crossing their rest position, as well as radio time signals. For magnetic field compensation, the apparatus was equipped with a control manometer and a Helmholz coil made in the Department in 1956. With this apparatus, measurements at the main points of the pendulum network of Poland were made between 1956 and 1959 with an accuracy of acceleration difference determination of the order of $\pm$ 0.2 mgal.

stup sejsmiczny = Seismic pole

stup grawimetryczny = Gravimetric pole

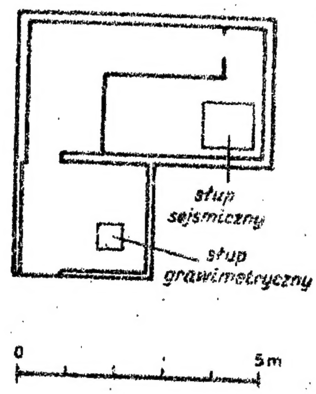

Fig. 3

3) Observations

In carrying out measurements between such distant points, special attention had to be given to the following: 1) The matter of appropriate transportation of pendulums, 2) The problem of achieving similar observation temperatures in both stations and applying thermal coefficients appropriate for the prevailing temperatures, and 3) The matter of developing an appropriate method and observation program which would properly solve the problem of the Time Service.

The pendulums were custom-packed for transportation with pneumatic cushions amortizing all vibrations and shocks.

Taking into consideration the low temperatures at the station chosen in Antarctica, the temperature of the observation station in Warsaw was lowered by opening windows two weeks prior to the start of observation. On completion of link observations, a special series of observations was carried out to establish thermal coefficients.

Forseeing difficulties in the reception of time signals in Antarctica, an observation program was adopted which permitted the determination of pendulum periods directly on the basis of radio time signals, even in the case when this signal was available only once every twenty-four hours. Measurements were made in sets of four observations of pendulum swing periods. Each set of observations lasted twenty-four hours. The intervals between the individual observations in a set were approximately 20 seconds. A set of observations carried out on the basis of some basic time signal had to register this time signal at least at the beginning and at the end. Registrations within a set could use other radio time signals or even a contact chronometer, which did not influence the accuracy

of determination of a mean period for the whole series in the time units of the basic signal. Apart from this, observations at both stations should be carried out using time signals of at least one common radio station.

The following number of sets of observations was carried out at the stations linked:

At the initial point, Warsaw, two independent sets of observations lasting six hours each were carried out before departure (Warsaw I) and upon returning (Warsaw II) using time signals broadcast by the DIZ radio station of the Geodetical Institute in Potsdam, compared simultaneously with GBR, ROR and FYP signals;

At the designated point in Antarctica, three sets of observations were carried out using GBR, RPT, RWM, ROR and TQC time signals. The duration of the individual observations, depending on the program of the time signals received, amounted to from four to eight hours, keeping the mean duration at six hours (Table 2 represents a detailed list of the observations carried out).

In this way, periods were obtained at both stations referring to the same three time signals of GBR, ROR, and FYP (TQC signals are broadcast from the same clock as FYP signals). RPT and RWM signals were considered as an additional control factor. The reception of a number of different signals is also of importance in this case because of the well-known phenomenon of delayed time signals.

All observations were carried out with a 15' initial amplitude and air pressure under the bell at 10mm of mercury. The mean observation temperatures at the stations were the following:

Warsaw I	+ 7.5°C
Antarctica	+ 3.6°C
Warsaw II	+ 9.2°C

All observations were carried out in a magnetic field compensated in the vertical direction. The intensity of the vertical component of the field was 0.41 Oe at the Warsaw station and 0.64 Oe at the Antarctica station. The magnetic compensation apparatus used ensures compensation in the area enclosing the pendulums with a 1% accuracy.

4) Corrections of the Periods Observed

Correction of the pendulum periods observed was carried out taking advantage of the known characteristics of the apparatus which we determined in past years. The following corrections were introduced:

4. 1. Reduction to an infinitely small amplitude:

$$\Delta T_a = A\left(\frac{a_p + a_K}{2}\right)^2\left[1 - \frac{1}{3}\left(\frac{a_p - a_K}{a_p + a_K}\right)^2\right]$$

where: a_p is the initial amplitude of the pair of pendulums in minutes of arc,

a_k is the final amplitude of the pair of pendulums in minutes of arc,

A is the empirically determined coefficient for the given apparatus

$$A = (-0.0312 \pm 0.017) \times 10^{-7} \text{ sec.}$$

The error of the reduction coefficient applied was reflected in the difference in Warsaw and Antarctica periods according to the formula:

$$m_e = \pm 0.0017 \Delta a^2$$

(where Δa^2 is the mean difference in squares of amplitudes at both stations), and amounts to:

$$m_a = \pm 0.03 \times 10^{-7} \text{ sec.}$$

4. 2. Correction due to temperature according to formula:

$$\Delta T_t = \alpha \cdot (t - 15^\circ C) + \alpha_{\Delta t} \cdot \Delta t$$

where: t is the mean observation temperature

Δt is the change of temperature per hour

α and $\alpha_{\Delta t}$ are empirically determined coefficients.

Thermal coefficients for the apparatus were being determined systematically since 1955 from observations at temperatures ranging from + 50°C to + 35°C. On completion of the observations of the Warsaw-Antarctica link, the determination of the thermal coefficient was repeated, using temperatures ranging from -7°C to + 35°C; this is a range which encompasses the temperatures of observations of the link. Table 1 represents the results obtained.

Table 1

Year	$\alpha_{1,5}$	$\alpha_{2,1}$	α average	$\alpha_{\Delta t}$
1955/56	2,80 ± 0,06	−1,58 ± 0.05	−2,19 ± 0,04	+2,4
1957	−2,54 ± 0,05	−1,76 ± 0,05	−2,15 ± 0,05	+2,5 ± 0,4
1958	−2,57 ± 0,05	−1,74 ± 0,05	−2,16 ± 0,05	—
1959	−2,48 ± 0,02	−1,89 ± 0,02	−2,18 ± 0,02	

The stability of coefficient q_{av} was a favorable factor. Coefficients from the last determination were used for correction of link observations. The error in the difference of periods Warsaw and Antarctica, considering the thermal correction carried out, amounts to:

$$m_t = \pm 0.02 \Delta t_{av}$$

Where Δt_{av} is the difference of mean temperatures at the station linked.

$$m t = \pm 0.09 \times 10^{-7} \text{ sec}$$

4. 3. Reduction to zero pressure was carried out according to formula:

$$\Delta T_d = k_1 d + k_2 \sqrt{d}$$

$$d = \frac{b}{1 + 0.00367\ t}$$

where b is the pressure in the bell in mm of mercury,

t is the air temperature in °C,

k_1, k_2 are empirical coefficients determined from observations under pressures of from 5 to 760 mm of mercury:

$$k_1 = (-0.793 \pm 0.003)\ 10^{-7} \text{ sec}$$

$$k_2 = (-4.34 \pm 0.09)\ 10^{-7} \text{ sec.}$$

The error of the difference in Warsaw and Antarctica periods, due to the reduction carried out, amounts to

$$m_d = \pm \sqrt{0.003^2\ \Delta d^2 + 0.09^2\ (\Delta \sqrt{d})^2}$$

where Δd is the difference of the mean pressures at the stations linked,

$\Delta \sqrt{d}$ is the mean difference of the roots of pressures

$$m_d = \pm 0.01 \times 10^{-7} \text{ sec}$$

4. 4. The correction due to the changing influence of the moon and the sun was calculated using formulae:

$\Delta T_{☾} = -0.136\ (3\cos^2 z - 1) \times 10^{-7}$ sec,

$\Delta T_{\odot} = -0.062\ (3\cos^2 z - 1) \times 10^{-7}$ sec.

The values of this correction are within the limits of from -0.1×10^{-7} seconds to $+ 0.2 \times 10^{-7}$ seconds, and the error m_g of its determination is smaller than $\pm 0.1 \times 10^{-7}$ seconds.

The correction due to the common vibration of the fulcrum was not included in the calculations. Good agreement of the periods of individual pendulums (within limits of 10^{-6} seconds) and good stability of the fulcrum ($s = 10^{-6}$ seconds) permitted neglecting this correction, since the error m_s arising from this is smaller than $\pm 0.1 \times 10^{-7}$ sec.

The correction due to the movement of the observation clock at the Warsaw station was determined from the comparisons of the DIZ working signals with GBR, ROR, and FYP signals; the correction obtained for all observations was equal to zero, with an accuracy of $\pm 0.1 \times 10^{-7}$ seconds. At the Antarctica station the periods determined on the basis of individual time signals are shown on Table 2, determination of the corrections ΔT_u being due to the working of individual clocks and errors in broadcasting of time signals. On the basis of the ΔT_u corrections, the error in the station mean in reference to the mean clock was evaluated as $\pm 0.12 \times 10^{-7}$ seconds. Taking into consideration the above errors in reductions due to the working of clocks and broadcasting time signals, their influence m_u on the difference of Warsaw and Antarctica periods was evaluated as $\pm 0.2 \times 10^{-7}$ sec.

5) Results and Analysis of Accuracy

The corrected period of the pair of pendulums is shown on Table 3, simultaneously giving average temperature and pressure.

From the agreement of results, the mean error in the single measurement of the period for a pair of pendulums was calculated as

$$m_o' = \pm 0.76 \times 10^{-7} \text{ sec}$$

and for the mean pendulum

$$M_o' = \pm 0.70 \times 10^{-7} \text{ sec.}$$

Table 2

Table of the Reduced Periods in Units of Received Time Signals

Location Antarctica $T = 0.495\ 24$

Se-ria	GBR			RPT			RWM			ROR			TQC			Śr.		
	Nr obs.	p	T 1–3 2–4	Nr obs.	p	T 1–3 2–4	Nr obs.	p	T 1–3 2–4	Nr obs.	p	T 1–3 2–4	Nr obs.	p	T 1–3 2–4	Nr obs.	p	T 1–3 2–4
I	1–4	4	81,5 75,5	1–4	4	80,6 74,7	1–4	4	80,6 74,8							1–4	4	80,9 75,0
	ΔT_u		–0,5			+0,3			+0,2									
II							5–7	3	80,6 75,4							5–7	3	80,7 75,5
	5–8	4	79,8 74,6	5–8	4	81,0 75,8				5–7	3	80,3 75,1						
							8	1	79.4 74,4							8	1	79,3 74,3
	śr.	4	79,8 74,6		4	81,0 75,8		4	80,3 75,2		3	80,3 75,1						80,4 75,2
	ΔT_u		+0,6			0,6			+0,1			+0,1						
III	9–10	2	80,3 75,6				9–11	3	80,1 75,4	9–11	3	79,7 75,1				9–10	2	80,0 75,3
				9–12	4	80,0 75,2							9–12	4	80,2 75,4	11	1	80,0 75,3
	11–12	2	80,6 75,8				12	1	80,8 75,9	12	1	80,0 75,5				12	1	80,4 75,7
	śr.	4	80,4 75,7		4	80,0 75,2		4	80,3 75,5		4	79,8 75,2		4	80,2 75,4			80,1 75,4
	ΔT_u		–0,3			+0,2			–0,2			+0,2			–0,1			

Table 3

Location	Date	Nr. ser.	Nr. obs.	t_{Lr}	b_{Lr}	p	Reduced Periods T: 1—3	v	2—4	v	Mean	v	$\Delta=(1-3)-(2-4)$	$V=\Delta_{Lr}-\Delta$
	1958						0,49555							
Warsaw I	6. XII	a	1	8,48	9,50	1	13,1	+0,1	07,5	+0,5	10,3	+0,3	+5,6	−0,7
			2	8,38	9,50	1	13,0	+0,2	08,5	−0,5	10,8	−0,2	+4,5	+0,4
	7. XII		3	7,96	9,50	1	13,5	−0,3	08,8	−0,8	11,2	−0,6	+4,7	+0,2
			4	8,05	9,52	1	11,5	+1,7	06,4	+1,6	09,0	+1,6	+5,1	−0,2
	8. XII		5	6,42	9,50	1	13,2	0,0	07,3	+0,7	10,2	+0,4	+5,9	−1,0
	8. XII	b	1	6,98	9,66	1	14,1	−0,9	08,8	−0,8	11,4	−0,8	+5,3	−0,4
	9. XII		2	7,11	9,70	1	13,8	−0,6	08,7	−0,7	11,2	−0,6	+5,1	−0,2
			3	7,21	9,78	1	12,7	+0,5	07,4	+0,6	10,0	+0,6	+5,3	−0,4
			4	7,04	9,80	1	13,7	−0,5	08,6	−0,6	11,2	−0,6	+5,1	−0,2
		Mean					13,2		08,0		10,6			
	1959						0,49524							
Antarctica	25—26. I	a	1—4	3,97	10,99	4	80,9	−0,5	75,0	+0,2	78,0	−0,2	+5,9	−1,0
	26—27. I	b	5—7	3,98	12,09	3	80,7	−0,3	75,5	−0,3	78,1	−0,3	+5,2	−0,3
	27. I		8	3,65	12,30	1	79,3	+1,1	74,3	+0,9	76,8	+1,0	+5,0	−0,1
	27—28. I	c	9—10	2,95	12,45	2	80,0	+0,4	75,3	−0,1	77,6	+0,2	+4,7	+0,2
	28. I		11	2,88	12,85	1	80,0	+0,4	75,3	−0,1	77,8	+0,2	+4,7	+0,2
			12	2,64	13,15	1	80,4	0,0	75,7	−0,5	78,0	−0,2	+4,7	+0,2
		Mean					80,4		75,2		77,8			
							0,49553							
Warsaw II	13. III	a	1	8,79	11,15	1	11,3	−0,3	08,1	−1,1	09,7	−0,7	+3,2	+1,7
			2	8,91	11,20	1	11,4	−0,4	08,0	−1,0	09,7	−0,7	+3,4	+1,5
	14. III		3	7,65	11,15	1	11,8	−0,8	07,9	−0,9	09,8	−0,8	+3,9	+1,0
			4	8,19	11,20	1	11,0	0,0	07,5	−0,5	09,2	−0,2	+3,5	+1,4
	17. III	b	1	9,23	14,10	1	11,1	−0,1	06,7	+0,3	08,9	+0,1	+4,4	+0,5
			2	10,22	14,20	1	10,7	+0,3	05,7	+1,3	08,2	+0,8	+5,0	−0,1
	18. III		3	9,52	14,25	1	10,7	+0,3	06,7	+0,3	08,7	+0,3	+4,0	+0,9
			4	10,78	14,40	1	09,7	+1,3	05,4	+1,6	07,6	+1,4	+4,3	+0,6
		Mean					11,0		07,0		09,0		+4,9	
		pvv						10,43		15,26		10,88		16,10

$$m_0' = \sqrt{\frac{[pvv]}{n-m}} = \sqrt{\frac{10,43+15,26}{46-6}} = \pm 0,76\cdot 10^{-7} \text{ sek}$$

$$M_0' = \sqrt{\frac{[pvv]}{n-m}} = \sqrt{\frac{10,88}{23-3}} = \pm 0,70\cdot 10^{-7} \text{ sek.}$$

$$m_0'' = \frac{[pVV]}{2(n-m)} = \sqrt{\frac{16,10}{2(23-3)}} = \pm 0,60\cdot 10^{-7} \text{ sek.}$$

The error m_0' is made up of random error μ and errors χ common in the given observation to both pairs of pendulums, which we call the systematic part of the error m_0'. From the relations

$$m_0'^2 = \mu^2 + \chi^2 = 0.584$$

$$M_0' = \frac{1}{2}\mu^2 + \chi^2 = 0.949$$

we obtain

$$\mu = \pm 0.42 \times 10^{-7} \text{ sec}, \qquad \chi = \pm 0.64 \times 10^{-7} \text{ sec}.$$

The mean error in a single measurement for a pair of pendulums was arrived at from the analysis of the relative changes of the pendulum periods during observations of the link (that is, from the analysis of the differences $\Delta = T_{1-3} - T_{2-4}$).

$$m_0^* = \pm 0.60 \times 10^{-7} \text{ sec}$$

Because Δ is free from the common error of both pairs of pendulums χ, the influence of this error was taken into account when calculating the mean error for the station mean M, with the result:

for the Warsaw station: $M_{W-wa} = \sqrt{\frac{m_0^{*2}}{16} + \frac{\chi^2}{8}} = \pm 0.27 \times 10^{-7}$ sec

for the Antarctica station:

$$M_{Ant} = \sqrt{\frac{m_0^{*2}}{24} + \frac{\chi^2}{12}} = \pm 0.22 \times 10^{-7} \text{ sec}$$

The analysis carried out above permits the statement to be made that there was good stability of pendulum periods during the observation cycle carried out.

An important criterion in evaluating the accuracy is the agreement of pendulum period on return to the same location. In this case, the time interval between observations at the linked points is quite long, and a question may arise as to whether the agreement of Warsaw I and Warsaw II periods is not just coincidental. Comparing these values with the mean periods of observations carried out at the Warsaw location for several years:

in 1957	T_{av} = 0.4955	509.8 seconds
in 1958		507.3
Warsaw I (link with Antarctica)		510.6
Warsaw II (link with Antarctica)		509.0

in 1959 508.0,

it is apparent that the yearly change in pendulum periods is only slightly greater than the difference between Warsaw II and Warsaw I periods. This difference may therefore be used to evaluate the accuracy of a precise measurement by a method independent of the analysis formerly carried out.

From the station means of pendulum pair periods and of the mean pendulum obtained, the difference in acceleration due to gravity between the linked points was calculated according to the formula

$$\underset{[\text{W-wa}=\text{Warsaw}]}{g_{\text{Ant}} - g_{\text{W-wa}}} = -\frac{2g_{\text{W-wa}}}{T_{\text{W-wa}}}(T_{\text{Ant.}} - T_{\text{W-wa}}) + \frac{3g_{\text{W-wa}}}{T^2_{\text{W-wa}}}(T_{\text{Ant}} - T_{\text{W-wa}})^2$$

The results are shown on Table 4.

Table 4

Station	T_{1-3} sek.	T_{2-4}	T. aver.	Δg mgal 1-3	v	2-4	v	average	v
Warsaw I	0,4955 513,2	08,0	10,6						
Antarctica	0,4952 480,4	75,2	77,8	1202,15	+0,32	1202,15	+0,32	1202,15	+0,32
Warsaw II	0,4955 511,0	07,0	09,0	1201,28	−0,55	1201,75	0,08	1201,52	−0,31
							Δg average	1201,83	

Turning to the evaluation of the accuracy of the calculated difference in acceleration, its mean error $m_{\Delta g}$ was determined on the basis of:

1) The analysis of the reduced periods and reduction errors

$$m_{\Delta g} = \frac{2g_{\text{W-wa}}}{T_{\text{W-wa}}} \cdot m\,(T_{Ant} - T_{\text{W-wa}})$$

$$m_{\Delta g} = \pm\, 0.4 \sqrt{M^2_{Ant} + \frac{1}{2} M^2_{\text{W-wa}} + m_a^2 + m_t^2 + m_d^2 + m_g^2 + m_s^2 + m_\mu^2 + m_k^2} \text{ mgal}$$

where M_{Ant}, $M_{\text{W-wa}}$ are the mean station errors in units of 10^{-7} seconds m_a, m_t, m_d, m_g, m_s, m_μ, are mean correction errors in units of 10^{-7} seconds and, m_k is the systematic component of the compensation error at one location, obtaining

$$m_{\Delta g} = \pm\, 0.18 \text{ mgal}$$

2) the divergence of results Δg obtained from pendulum pairs $m_{\Delta g} = \pm\, 0.21$ mgal

3) the divergence of the mean result of the observations "there" and "back":

$$m_{\Delta g} = \pm 0.32 \text{ mgal}$$

The excellent agreement of the results of analyses undertaken should be emphasized, as it is a basis for accepting the error, specifying the accuracy of measurement as ± 0.3 mgal. Thereby, the end result of the measurements may be given as

$$g_{Ant} - g_{W\text{-}wa} = + 1201.8 \text{ mgal} \pm 0.3 \text{ mgal.}$$

The acceleration due to gravity in the Potsdam system

$$g_{Pots} = 981\ 274.0 \text{ mgal}$$

given by the Institute of Geodesy and Cartography for the initial point Warsaw amounts to

$$g_{W\text{-}wa} = 981\ 236.6 \text{ mgal}$$

The accuracy of this value may be accepted as ± 0.15 mgal; therefore, the acceleration due to gravity in the designated point in Antarctica related to the Potsdam system amounts to

$$g_{Ant} = 982\ 438.4 \text{ mgal} \pm 0.4 \text{ mgal.}$$

Taking into account the free air correction, we obtain an acceleration reduced to sea level

$$g_o = 982\ 449.3 \text{ mgal}$$

and a free air (Faye) anomaly in relation to the normal acceleration according to the formula of 1930

$$g_o - \gamma_o = + 68.5 \text{ mgal.}$$

Taking into consideration the excellent conditions under which the observations were carried out, it can be said that the high accuracy obtained corresponds to the accuracy obtained with this apparatus when measuring the basic pendulum network in Poland. The newly-designated point at the A. B. Dobrowolski station can be one of the principal points of the gravimetric network of Antarctica also from the point of view of its stable location on rock; this is of basic importance under Antarctica conditions.

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